

MINERALOGY, PETROLOGY AND OXYGEN FUGACITY OF THE LAPAZ ICEFIELD LUNAR BASALTIC METEORITES AND THE ORIGIN OF EVOLVED LUNAR BASALTS.

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Introduction: LAP 02205 is a 1.2 kg lunar mare basalt meteorite found in the Lap Paz ice field of Antarctica in 2002 [1]. Four similar meteorites were also found within the same region [1] and all five have a combined mass of 1.9 kg (LAP 02224, LAP 02226, LAP 02436 and LAP 03632, hereafter called the LAP meteorites). The LAP meteorites all contain a similar texture, mineral assemblage, and composition. A lunar origin for these samples comes from O isotopic data for LAP 02205 [1], Fe/Mn ratios of pyroxenes [1-5], and the presence of distinct lunar mineralogy such as Fe metal and baddeleyite. The LAP meteorites may represent an area of the Moon, which has never been sampled by Apollo missions, or by other lunar meteorites. The data from this study will be used to compare the LAP meteorites to Apollo mare basalts and lunar basaltic meteorites, and will ultimately help to constrain their origin.

Samples and analyses: Four sections of the LAP meteorites (LAP 02205, 30; LAP 02224, 17; LAP 02226, 18; LAP 02436, 17) were examined using a petrographic microscope, and a Cameca SX100 electron microprobe at the Johnson Space Center. Modal analyses of the meteorites were determined using 1024 x 1024 pixel x-ray maps (for Si, Ti, Al, Fe, Cr, Ca, Mg, and P) and analyzed using image-processing in IDL. Plagioclase, ilmenite, pyroxene, olivine and spinel modes were determined using Al, Ti, Ca, Mg and Cr, respectively. The microprobe was calibrated with natural (kaersutite, wollastonite, chromite, rutile, olivine) and synthetic (Fe metal, Ni metal, phosphide) standards, analysis was carried out using 15 kV accelerating voltage and 20 nA sample current. Together with the modal analyses, the mineral major element data (averages for each phase) were used to calculate bulk compositions. Raman spectra on silica phases were obtained using a Jobin Yvon Labram HR with 2048 CCD. The 633 nm line of a HeNe laser was focused to an area of ~ 1 μm^2 on the sample surface through an Olympus BX-41 optical microscope attached to the spectrometer. Laser power was 17 mW on the surface of the sample, and spectra were accumulated over 500 to 600 s, to maximize the signal to noise ratio. The wavenumber position of the raman peak was calibrated using the 520.5 cm^{-1} line of Si metal. A raman spectrum on a silica grain in LAP 02226 (section ,18) was collected with a x100 ULWD objective, for 500 seconds, using a 632.817 excitation line and 1800 grating. Spectral width was 1.28 cm^{-1} , and the range counted was 25 to 500 cm^{-1} .

Textures and Mineralogy: The LAP meteorites are all medium to coarse-grained subophitic basalts, with sparse olivine phenocrysts (range from Fo₅₃ to Fo₆₂ in the cores and Fo₄₆ to Fo₅₇ in the rims) and groundmass dominated by pyroxene, plagioclase and ilmenite. The pyroxene is either intersertile or enclosing plagioclase within all of the rocks,

and has strong chemical variation from orthopyroxene to pigeonite. Plagioclase laths are a dominant component in the LAP meteorites, ranging from 32.9 to 39.3 modal % and from An₈₅ to An₈₉. Ilmenite is the most dominant opaque (5 to 7.6 modal %) with very low MgO content (0.02 to 0.24 wt. %). All four meteorites contain a criss-crossing network of thin melt veins, which are typically brown in plane polarized light, but can be variable in color. Back scattered electron images of these veins show their irregular shape, compositional banding, and also the small mineral inclusions that contribute to the heterogeneity. Each meteorite also contains small to trace amounts of olivine, spinel, metal, sulfide, baddeleyite, phosphate, silica and melt veins.

Discussion

Shock state: The similar composition of the melt veins and the bulk rock indicates that these veins are likely caused by shock melting. A shock event resulted in small volume melts that infiltrated as veins within regions of each rock. This is consistent with the minimal shock effects observed in the crystals — there is only slight undulatory extinction within plagioclase grains but no more than has been observed in un-shocked terrestrial basalts. In addition, silica was identified as cristobalite using Raman spectroscopy; the peaks observed at 112, 230 and 415 cm^{-1} all correspond to the major cristobalite raman peaks [6]. Cristobalite is stable at <1 GPa and between 1450°C and 1700°C, higher than liquidus temperatures calculated using MELTS (1159°C to 1206°C). Observations from impact localities where cristobalite is present suggest that it is formed by inversion from a higher pressure form of silica, such as stishovite or coesite (e.g., Popigai impact crater; [7]). It is likely therefore that cristobalite formed metastably within the LAP meteorites, being inverted from stishovite or coesite that formed as a result of shock.

Cooling rates: From the subhedral to skeletal morphology of the olivine it can be inferred that the basalts cooled between 0.1 –1 °C/hr [8]. In addition, the thickness of the plagioclase laths varies from 100 to 200 microns, bracketing the cooling rates between 0.5 and 2 °C/hr [9]. Textural comparison of these rocks with other terrestrial and Apollo samples suggest that they are slowly cooled melts which formed at the lunar surface in the middle of a basalt flow between 2-10 m thick [8].

Oxygen Fugacity: Oxygen fugacity is an important variable in planetary basalts that has a fundamental control on properties such as olivine composition, mineral stability, and metal saturation. Olivine-liquid equilibria is fO₂ dependent and can place constraints on the oxygen fugacity at which an olivine basalt crystallized. Using the expression of [10] to estimate the ferric/ferrous iron ratio in the bulk composition, the olivine-liquid Kd of 0.34 from [11], and the temperature for the liquidus of the averaged bulk composi-

tion (1185 °C), we calculate that the average olivine composition of the four meteorites (Fo_{58}) will be in equilibrium with the bulk rock composition at an oxygen fugacity of IW-1.

Oxygen fugacity can also be determined by considering two additional equilibria that are represented in all four samples: $Fe + SiO_2 + O_2 = Fe_2SiO_4$ (iron-silica-fayalite) and $Fe + FeTiO_3 + 1/2 O_2 = Fe_2TiO_4$ (iron-ilmenite-ülvospinel). The metal, ilmenite, silica and olivine are nearly pure, thus the activities of each of these components are close to unity. However, since ülvospinel is a minor component of the spinel phase, its activity has been calculated [12]. Combining activities and thermodynamic data [from 13, 14], yields calculated log fO_2 values of 1 log fO_2 unit below the IW buffer at 1185 °C, in agreement with fO_2 data from other lunar material [15] (Figure 1). The presence of metallic iron within the samples also supports the conclusion of a reduced lunar mantle below the IW oxygen buffer. The question of whether the reducing conditions originated within the crust or mantle of the Moon or during magma evolution cannot be addressed, but there is not a significant deviation from mantle oxygen fugacities with fractionation of more primitive basaltic lavas.

Temperature and Bulk Composition: Application of the MgO thermometer [18] yields a range of temperatures from 1107 to 1145 °C. The spinel inclusions in olivine phenocrysts allow application of the olivine-spinel thermometer (based on Fe/Mg partitioning between these two phases, [19]); temperature based on this technique, and using spinel and olivine compositions from LAP 02205, is 1175 °C. Finally, a thermometer based on olivine-liquid partitioning of FeO and MgO can be applied to basaltic rocks with very small amounts of olivine phenocrysts such as the LAP meteorites [11]. Using the average olivine composition from all four meteorites, together with the average bulk composition from all four, this thermometer gives a temperature of 1185 °C. All of these estimates show that this is indeed a low temperature basalt and likely a product of fractionation of a more primitive basaltic liquid.

TiO₂ compositions of the LAP meteorites are similar to Apollo 12 ilmenite basalts; they plot within the upper range of the low-Ti lunar samples. Interestingly, they also show relatively high Al₂O₃ but seem to be depleted in MgO compared to the other lunar samples. High alumina basalts, 14063 and 14053 [16,17], differ from the LAP meteorites in that their bulk MgO is much higher. It is clear that the LAP meteorites are unique basalts not sampled by Apollo. This bulk composition is low in MgO and high in Al₂O₃, also consistent with a more fractionated liquid that may have been derived at lower temperatures.

Finally, in order to test whether the LAP composition can be derived from any known lunar parental liquids, we have carried out fractional crystallization calculations using several low TiO₂ mare basalt liquids (12006, 12008, 12075, and 15672) and the MELTS application [20]. These calculations show that the LAP meteorites have evolved as a result either of low pressure fractional crystallization, or as fractional crystallization coupled with assimilation of anorthosite; both scenarios start with a low Ti, high Mg basaltic parent.

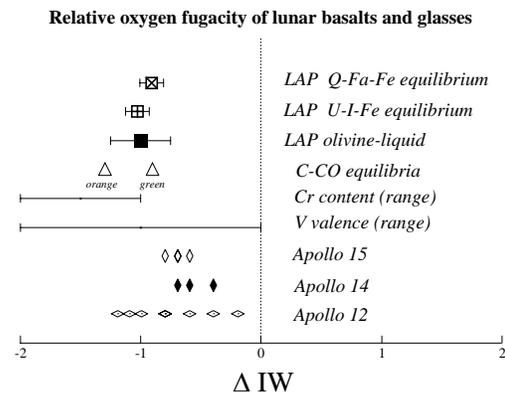


Figure 1: Oxygen fugacity (relative to the iron-wüstite buffer) calculated for the LAP meteorites as discussed in text. Comparison is made to other lunar samples; data from [15 and 21-24].

- References:** [1] Ant. Met. News. (2003) vol. 26, No. 2; [2] Righter, K. et al. (2004) LPSC XXXV, #1667; [3] Joy, K. et al. (2004) LPSC XXXV, #1545; [4] Anand, M. et al. (2004) LPSC XXXV, #1626; [5] Korotev, R.L. et al. (2004) LPSC XXXV, #1416; [6] Kingma, K.L. and Hemley, R.E. (1994) Amer. Mineral. 79, 269-273; [7] El Goresy, A. et al. (2002) LPSC XXXIII, #1031; [8] Lofgren, G.E. et al. (1975) PLSC 6th, 79-99; [9] Grove, T.L. and Walker, D. (1977) PLSC 8th, 1501-1520; [10] Kress, V.C. and Carmichael, I.S.E. (1991) CMP 108, 82-92; [11] Roeder, P.L. (1974) EPSL 23, 397-410; [12] Sack, R.O. and Ghiorso, M.S. (1991) 106, 474-505; [13] O'Neill, H.St.C. (1987) Amer. Mineral. 72, 67-75; [14] O'Neill, H.St.C. et al. (1988) GCA 52, 2065-2072; [15] Sato, M. et al. (1973) PLSC 4th, 1061-1079; [16] Kushiro, I. et al. (1972) PLSC 3rd, 115-129; [17] Ridley, W.I. (1975) PLSC 6th, 131-145; [18] Jones, J.H. (2003) LPSC XXXIV, #1130; [19] Sack, R.O. and Ghiorso, M.S. (1991) Amer. Mineral. 76, 827-847; [20] Ghiorso, M.S. and Sack, R.O. (1995) CMP 119, 197-212; [21] Karner, J.M. et al. (2004) LPI Contrib. No. 1203, 35; [22] Delano, J.W. (2001) Origins Life Evol. Biosph. 31, 311-341; [23] Weitz, C.M. et al. (1997) GCA 61, 2765-2775; [24] Fogel, R. and Rutherford, M.J. (1995) GCA 59, 201-215.